Int J Life Cycle Assess (2013) 18:683–697
DOI 10.1007/s11367-012-0489-5

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Identifying best existing practice for characterization modeling in life cycle impact assessment

Michael Z. Hauschild · Mark Goedkoop · Jeroen Guinée · Reinout Heijungs · Mark Huijbregts · Olivier Jolliet · Manuele Margni · An De Schryver · Sebastien Humbert · Alexis Laurent · Serenella Sala · Rana Pant

Received: 18 January 2012 / Accepted: 15 August 2012 / Published online: 12 September 2012

Abstract
Purpose Life cycle impact assessment (LCIA) is a field of active development. The last decade has seen prolific publication of new impact assessment methods covering many different impact categories and providing characterization factors that often deviate from each other for the same substance and impact. The LCA standard ISO 14044 is rather general and unspecific in its requirements and offers little help to the LCA practitioner who needs to make a choice. With the aim to identify the best among existing characterization models and provide recommendations to the LCA practitioner, a study was performed for the Joint Research Centre of the European Commission (JRC).

Methods Existing LCIA methods were collected and their individual characterization models identified at both midpoint and endpoint levels and supplemented with other environmental models of potential use for LCIA. No new developments of characterization models or factors were done in the project. From a total of 156 models, 91 were short listed as possible candidates for a recommendation within their impact category. Criteria were developed for analyzing the models within each impact category. The criteria addressed both scientific qualities and stakeholder acceptance. The criteria were reviewed by external experts and stakeholders and applied in a comprehensive analysis of the short-listed characterization models (the total number of

Electronic supplementary material The online version of this article (doi:10.1007/s11367-012-0489-5) contains supplementary material, which is available to authorized users.

M. Z. Hauschild (✉) · A. Laurent
Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark (DTU), Produktionstorvet, Building 426,
2800 Lyngby, Denmark
e-mail: mzha@dtu.dk

M. Goedkoop · A. De Schryver
PRé Consultants B.V.,
Printerweg 18,
3821 AD Amersfoort, The Netherlands

J. Guinée · R. Heijungs
Institute of Environmental Sciences (CML), Department of Industrial Ecology, Faculty of Science, Universiteit Leiden, Leiden, The Netherlands

M. Huijbregts
Department of Environmental Science,
Radboud University Nijmegen,
P.O. Box 9010, 6500 GL Nijmegen, The Netherlands

O. Jolliet
Department of Environmental Health Sciences,
School of Public Health, University of Michigan,
Ann Arbor, MI 48109, USA

M. Margni
Department of Mathematical and Industrial Engineering, CIRAIG, École Polytechnique de Montréal,
2900 Édouard-Montpetit,
Montréal, Québec H3C 3A7, Canada

O. Jolliet · M. Margni · S. Humbert
Quantis International,
Parc scientifique EPFL, Bât. D,
CH-1015 Lausanne, Switzerland

S. Sala · R. Pant
Sustainability Assessment Unit, Institute for Environment and Sustainability, European Commission-Joint Research Centre,
Via Enrico Fermi 2749,
21027 Ispra, VA, Italy

criteria varied between 35 and 50 per impact category). For each impact category, the analysis concluded with identification of the best among the existing characterization models. If the identified model was of sufficient quality, it was recommended by the JRC. Analysis and recommendation process involved hearing of both scientific experts and stakeholders.

Results and recommendations Recommendations were developed for 14 impact categories at midpoint level, and among these recommendations, three were classified as "satisfactory" while ten were "in need of some improvements" and one was so weak that it has "to be applied with caution." For some of the impact categories, the classification of the recommended model varied with the type of substance. At endpoint level, recommendations were only found relevant for three impact categories. For the rest, the quality of the existing methods was too weak, and the methods that came out best in the analysis were classified as "interim," i.e., not recommended by the JRC but suitable to provide an initial basis for further development.

Discussion, conclusions, and outlook The level of characterization modeling at midpoint level has improved considerably over the last decade and now also considers important aspects like geographical differentiation and combination of midpoint and endpoint characterization, although the latter is in clear need for further development. With the realization of the potential importance of geographical differentiation comes the need for characterization models that are able to produce characterization factors that are representative for different continents and still support aggregation of impact scores over the whole life cycle. For the impact categories human toxicity and ecotoxicity, we are now able to recommend a model, but the number of chemical substances in common use is so high that there is a need to address the substance data shortage and calculate characterization factors for many new substances. Another unresolved issue is the need for quantitative information about the uncertainties that accompany the characterization factors. This is still only adequately addressed for one or two impact categories at midpoint, and this should be a focus point in future research. The dynamic character of LCIA research means that what is best practice will change quickly in time. The characterization methods presented in this paper represent what was best practice in 2008–2009.

Keywords Best practice · Characterization · Endpoint · Impact indicator · International Reference Life Cycle Data System (ILCD) · Life cycle impact assessment · Midpoint

1 Introduction

Characterization or "calculation of impact category indicator results" is defined by the ISO 14044 standard for Life Cycle Assessment as the mandatory third element of the life cycle impact assessment phase (ISO 2006). Here, the potential impact from each inventory emission to—and/or resource flow from—the environment is modeled quantitatively according to the relevant environmental mechanism using a characterization model. The characterization model calculates substance-specific characterization factors that express the potential impact of each single elementary flow in terms of the common unit of the category indicator. Characterization factors thus allow comparing the different elementary flows quantitatively in terms of their ability to contribute to the impact category indicator—they give a relative expression of the potency of each elementary flow. Within the life cycle impact assessment, characterization factors are multiplied with inventory data, and the outcome is category indicator results, expressed in a unit common to all contributions within the impact category (e.g., kilogram CO_2-equivalents for greenhouse gases contributing to the impact category climate change).

The collection of individual characterization models (each addressing their separate impact category) is referred to as a "life cycle impact assessment (LCIA) method" (e.g., the CML 2002 method or the IMPACT 2002+ method).

The ISO 14044 standard recommends that "the impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body." Obvious examples of characterization factors that met this requirement at the time of writing the standard are the ozone depletion potentials (ODP, produced by the World and Global Meteorological Organisation, WMO) applied at the midpoint level for the impact category stratospheric ozone depletion and the global warming potentials (GWP, produced by the Intergovernmental Panel on Climate Change, IPCC; latest update, Forster et al. 2007) for the climate change midpoint impact category. These remain even today the most obvious examples of characterization factors that satisfy the ISO standard's recommendation to apply internationally accepted models and factors, which illustrates the modest activity on international harmonization and scientific consensus building for other impact categories.

Attempts have been made in consecutive working groups and task forces on life cycle impact assessment under the Society of Environmental Toxicology and Chemistry (SETAC) (e.g., Udo de Haes et al. 1999, 2002) and later under the UNEP-SETAC Life Cycle Initiative (e.g., Jolliet et al. 2004), but they have not resulted in a uniform globally accepted set of characterization models and factors. The most promising results have been a broader consensus on the need to merge midpoint and endpoint models in a consistent framework to combine the advantages of both concepts (Bare et al. 1999, 2000) and the development of

a generic set of quality criteria for good practice in characterization modeling (Margni et al. 2007; Udo de Haes et al. 2002). For the impact categories on human toxicity and ecotoxicity, these activities resulted in the development of a scientific consensus characterization model, USEtox™ (Hauschild et al. 2008; Rosenbaum et al. 2008).

In parallel, numerous life cycle impact assessment methods have been developed and applied in LCA studies, e.g., CML 2002 (Guinée et al. 2002), Eco-indicator 99 (Goedkoop and Spriensma 2000), EDIP 2003 (Hauschild and Potting 2005), EPS (Steen 1999a, b), IMPACT 2002+ (Jolliet et al. 2003), LIME (e.g., Itsubo et al. 2004), LUCAS (Toffoletto et al. 2007), ReCiPe (Goedkoop et al. 2009), and TRACI (Bare et al. 2003). The development has gone from dedicated midpoint methods (CML 2002, EDIP 2003, TRACI) and endpoint methods (EPS, Eco-indicator 99) towards methods that try to combine the two approaches and model impacts at both mid- and endpoint levels (LIME, ReCiPe, IMPACT2002+). None of these methods can be said to enjoy the international acceptance that the ISO standard calls for, and the LCA practitioner is thus left with a poorly guided choice among different characterization models and factors that for some of the impact categories give very different results when applied (Dreyer et al. 2003; Pant et al. 2004; Pizzol et al. 2011a, b).

In this setting, the Joint Research Centre (JRC) of the European Commission has launched the International Reference Life Cycle Data System (ILCD) to develop technical guidance that complements the ISO Standards for LCA and provides the basis for greater consistency and quality of life cycle data, methods, and LCA studies. Inherent in this goal is to develop recommendations of best practice characterization framework, models, and factors. An evaluation was performed of existing LCIA methods and characterization models with the aim to identify the best existing practice. Through a consultation process involving hearing of both scientific experts and stakeholders, the evaluation formed the basis of recommendations of characterization models and factors for impact categories mainly at midpoint but also at endpoint level. The paper reports on both the evaluation process and the recommendations. The detailed results of the project are available from the JRC in the form of three technical reports (EC-JRC 2010a, b and EC-JRC 2011)

2 Methods

It has been the aim for each impact category to identify the best among existing characterization models. The first activity was therefore to identify available characterization models as they are used by the different LCIA methods. Figure 1 illustrates the characterization framework addressing both midpoint and endpoint and shows the impact categories for which the methodology was deemed sufficiently mature to support an identification of best practice and development of recommendations (EC-JRC 2010a) and that have been covered by the ILCD at midpoint and endpoint levels.

Impact categories at the midpoint level are ideally defined by an indicator placed at the location in the impact pathway up to which a common mechanism exists for the main contributing substances within that specific impact category. In the example climate change, the midpoint indicator is chosen at the level of increase in the radiative forcing of the atmosphere, because the pathways differ between greenhouse gases before that point, but are identical beyond that point and all the way to the areas of protection. For other impact categories, such as human toxicity and ecotoxicity, that are more heterogeneous in terms of impact pathway, there is no true midpoint as the fate, exposure, and effect steps of the impact assessment are all chemical specific. The chosen midpoint for these impact categories therefore lies close to the area of protection, and the endpoint modeling simply consists in characterizing the severity of the damage that is modeled by the midpoint indicator.

There are different classifications of areas of protection (ISO 14044; Udo de Haes et al. 1999; Steen 1999a, b). Within this study, three areas of protection were considered, namely human health, natural environment, and natural resources.

After identifying and preselecting candidates among existing characterization models in the first phase, the next phase developed criteria for each impact category, representing requirements to a good characterization model in terms of its scientific foundation and its acceptance among central stakeholders. In the third and final phase, the criteria were applied to the short-listed candidates, the best existing practice was identified and classified according to its level of maturity, and major shortcomings and research needs were identified for each impact category.

All three phases involved a review performed by external experts of relevance to each impact category, hearings of experts from the European Commission's advisory groups with LCIA specialist and business representatives, and consultation with national and international bodies and LCA stakeholders in general as illustrated in Table S1 and S2 of the Electronic supplementary material. Developers of LCIA methods were consulted on the short listing of methods, the development of criteria and analysis procedure, and the analysis of their methods using the criteria. The provided comments were processed interactively throughout the project, and the processing was documented in written form to

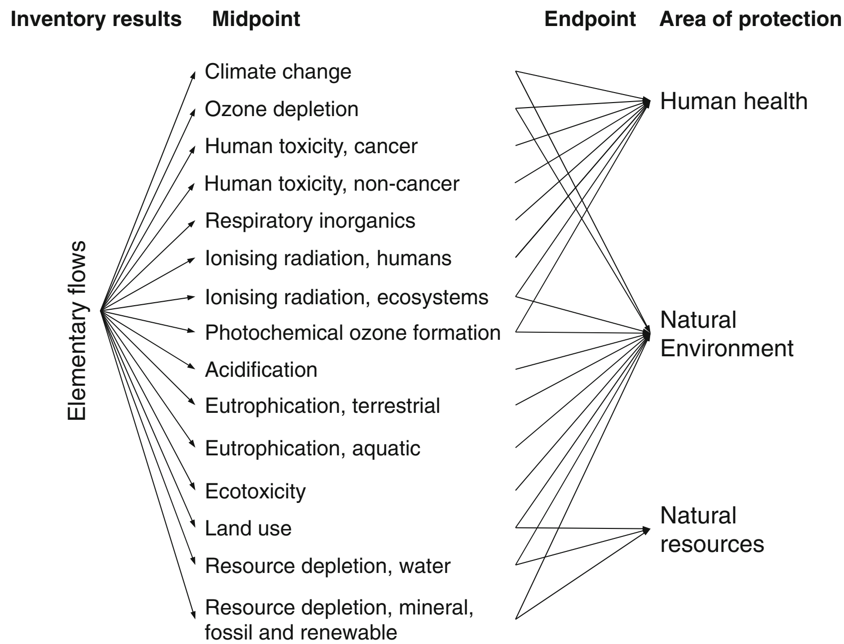

Fig. 1 Framework of the ILCD characterization linking elementary flows from the inventory results to indicator results at midpoint level and endpoint level for 15 midpoint impact categories and 3 areas of protection (taken from EC-JRC 2010b)

the EC-JRC.[1] The results from each phase of the project have been reported in three separate JRC reports (EC-JRC 2010a, b and EC-JRC 2011).

2.1 Short listing of methods

A survey was done of existing LCIA methods and individual impact assessment models with potential to serve as characterization model for an impact category. A total of 156 characterization models were identified belonging to 12 different LCIA methods. From these, 91 models were short-listed for further analysis by excluding

- Repetitions, i.e., same methods used in multiple LCIA methods. Here, only the most recent version was short listed, unless there was a better coverage of elementary flows in previous versions.
- Methods that were duplicated in forms adapted to different geographical regions without improving or changing them, apart from the regional parameterization.

Additionally, 14 environmental assessment models were identified that were not applied in any of the LCIA methods but deemed to have potential to serve as characterization models for some of the impact categories. Table S2 in the Electronic supplementary material gives an overview of the shortlisted characterization models.

2.2 Development and application of criteria

The analysis of the short-listed characterization models applied a comprehensive set of criteria that was developed in advance, building on previous work of SETAC LCIA working groups (Udo de Haes et al. 2002) and task forces under the Life Cycle Impact Assessment program under the first phase of the UNEP-SETAC Life Cycle Initiative (e.g., Margni et al. 2007). Criteria were developed prior to, and independent of, the analysis of the characterization models to make the criteria as objective as possible and minimize the risk of biasing the results in favor of a specific characterization model. Furthermore, the criteria were reviewed prior to application by domain experts and LCIA method developers whose methods were included among the short-listed methods. Criteria were developed for all impact categories at midpoint and endpoint levels, addressing both scientific quality and stakeholder acceptance or policy relevance.

Scientific criteria assessed

1. *Completeness of scope*—how well does the indicator and the characterization model cover the environmental

[1] It is a classical dilemma of research evaluation that in order to have competent assessors, you run the risk that they have stakes in what they are evaluating. In the process, we tried to balance the potential bias by

1. Submitting the preselection of characterization models to review among all members of the LCIA method developers advisory group to the European LCA Platform
2. Developing the criteria prior to the evaluation of the existing models and submitting first the criteria and later the evaluation results to peer review among domain experts for each impact category and among LCIA method developers whose methods were assessed and who were not represented in the project team
3. Submitting all results to an open stakeholder consultation before finalization and publication.

   Table S2 of the Electronic supplementary material shows the representation of method developers behind all the considered methods and models in the project team and in the expert and stakeholder consultations.

mechanisms associated with the impact category under assessment?

2. *Environmental relevance*—to what extent are the critical parts of the impact pathway included and modeled in accordance with the current state of the art?
3. *Scientific robustness and certainty*—how well has the model been peer reviewed, does it represent state of the art, can it be validated against monitoring data, and are uncertainties reported?
4. *Documentation*, *transparency*, *and reproducibility*—how accessible are the model, the model documentation, the characterization factors, and the applied input data?
5. *Applicability*—are characterization factors provided for the important elementary flows for this impact category in a form that is straightforward to apply?

The stakeholder acceptance criteria assessed aspects like endorsement of the model by competent authorities and understandability of the model principles and applied metric for users of the LCA results.

Each of these criteria was further detailed into a set of subcriteria. Many subcriteria were general and applied for each impact category (see Table S3 of the Electronic supplementary material), but for the scientific criteria on *environmental relevance and scientific robustness and certainty*, the subcriteria were developed specifically for each impact category reflecting the central characteristics of the underlying impact pathway.[2] An analysis of the impact pathway of each category helped identify key processes or aspects that should be considered in the characterization modeling, and these were the basis of formulating the category-specific subcriteria (flow sheets for each impact category can be found in EC-JRC 2010b).

The specific subcriteria developed for each of the impact categories are listed in the Electronic supplementary material S3.3. The procedure for evaluating a characterization model against the criteria is described in the Electronic supplementary material S3.1.

The criteria development resulted in 35–50 subcriteria for each impact category. While considerable effort was put into developing the criteria and applying them to the 91 short-listed characterization models, it became clear that the scoring of the models against the criteria should be taken as guiding and structuring the analysis and the comparison of the characterization models rather than as *being* the comparison. The main value of the exercise lay in the detailed insight it gave in the behavior and performance of each of the characterization models by forcing the analyst to investigate them all using the same criteria. In that sense, it was the comment given in text describing how the model met the criterion rather than the formal score that helped identify the best performing models. Often, there were trade-offs between the criteria in the sense that poor performance in one criterion was compensated by superior performance in another. The recommendation that came out of the evaluation was based on an expert judgment taking into account the performance against the totality of criteria. No attempts were made to develop a formalized weighting between the criteria, apart from identifying a few criteria as being of high importance to the impact category in question and setting requirements to a minimum performance for some of the central criteria (see Electronic supplementary material S3.1). As indicated by the number of criteria and the level of detail that they give the analysis, the scientific quality of the model was weighted higher than the stakeholder acceptance.

2.3 Identification of the best existing practice

The evaluation resulted in identification of the best among the existing characterization models at midpoint and endpoint level for each of the impact categories shown in Fig. 1. The quality of the selected characterization model was assessed and three levels of recommendation were distinguished:

I. Recommended and satisfactory
II. Recommended but in need of some improvements
III. Recommended but to be applied with caution

For many of the impact categories at endpoint, it was found that even if the best among existing characterization models could be identified, this model was still not seen as mature for recommendation, and it was then classified as "*Interim*." In case not even the best among existing characterization models could be identified, no model was highlighted for the impact category, neither as "recommended" nor as "interim." This did not mean the impact category was not seen as relevant, but that more methodological development efforts were needed before a recommendation or just a classification as interim could be given to any of the models.

For each impact category, some of the major research needs for the characterization modeling at midpoint and endpoint levels were identified (EC-JRC 2011).

3 Results and recommendations

The criteria, the analysis, and the resulting recommendations have undergone extensive external consultation and review as illustrated in Table S1.The results of the analysis are summarized in Tables 1 and 2.

The results of the analysis and the resulting recommendation and classification are described in the following

[2] For the category on resource depletion, the environmental relevance criterion was taken to address the coverage of the critical parts of the impact pathway leading from resource use towards damage to the Area of Protection Resources.

Table 1 Best available characterization models at midpoint

Impact category	Best among existing characterization models	Indicator	Classification
Climate change	Baseline model of 100 years of the IPCC (Forster et al. 2007)	Radiative forcing as global warming potential (GWP100)	I
Ozone depletion	Steady-state ODPs from the WMO assessment (Montzka and Fraser 1999)	Ozone depletion potential (ODP)	I
Human toxicity, cancer effects	USEtox model (Rosenbaum et al. 2008)	Comparative toxic unit for humans (CTU_h)	II/III
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al. 2008)	Comparative toxic unit for humans (CTU_h)	II/III
Particulate matter/respiratory inorganics	Compilation in Humbert (2009) based on Rabl and Spadaro (2004) and Greco et al. (2007)	Intake fraction for fine particles (kg PM2.5-eq/kg)	I/II
Ionizing radiation, human health	Human health effect model as developed by Dreicer et al. (1995) (ref. Frischknecht et al. 2000)	Human exposure efficiency relative to U^{235}	II
Ionizing radiation, ecosystems	Screening Level Ecological Risk Assessment (Garnier-Laplace et al. 2008) based on AMI model from Payet (2004)	Comparative toxic unit for ecosystems (CTU_e)	Interim
Photochemical ozone formation	LOTOS-EUROS as applied in ReCiPe (Van Zelm et al. 2008)	Tropospheric ozone concentration increase	II
Acidification	Accumulated exceedance (Seppälä et al. 2006; Posch et al. 2008)	Accumulated exceedance (AE)	II
Eutrophication, terrestrial	Accumulated exceedance (Seppälä et al. 2006; Posch et al. 2008)	Accumulated exceedance (AE)	II
Eutrophication, aquatic	EUTREND model as implemented in ReCiPe (Struijs et al. 2009b)	Residence time of nutrients in freshwater (P) or marine end compartment (N)	II
Ecotoxicity, freshwater	USEtox model, (Rosenbaum et al. 2008)	Comparative toxic unit for ecosystems (CTU_e)	II/III
Land use	Model based on soil organic matter (SOM) (Milà i Canals et al. 2007)	Soil organic matter	III
Resource depletion, water	Model for water consumption as in the Swiss ecoscarcity (Frischknecht et al. 2008)	Water use related to local scarcity of water	II
Resource depletion, mineral and fossil	CML 2002 (Guinée et al. 2002)	Scarcity	II

Models that are classified as level I, II, or III are recommended under the ILCD. A mixed classification is related to the application of the classified method to different types of substances

sections. Summaries of the analysis results for the main criteria are shown in Section S4 of the Supporting information.

The scores for the main criteria given to the models that were identified as the best among the existing in Tables 1 and 2 are summarized in Tables 3 and 4 to show the frequencies of each score at midpoint and endpoint level. Although, as described earlier, the scoring should not be interpreted too rigidly, it is clear that the midpoint models across the scientific and stakeholder acceptance criteria have the majority of the scores in the A and B (full compliance or compliance in all essential aspects) and hence perform considerably better than the endpoint models where only partial or little compliance is observed for more criteria across the models

The characterization factors that are provided by the recommended characterization models have been made available in spreadsheet format from the ILCD homepage (http://lct.jrc.ec.europa.eu/).

3.1 Climate change

The GWP published by the Intergovernmental Panel on Climate Change (Forster et al. 2007) is the only method considered in the evaluation on midpoint level. It is based on the most up to date and scientifically robust consensus-based model available, with described and calculated uncertainties. There are three versions of the method, spanning different timeframes. In policy papers, usually, the 100-year timeframe is used and therefore chosen as best available, classified as level I (recommended and satisfactory). However, from a scientific/sustainability point of view, it may be preferred to use the 500-year time horizon, as in this case, additional relevant impacts are captured. The most appropriate among all models for characterization at endpoint level is the characterization model developed under ReCiPe, but it is classified as immature for recommendation (interim). This midpoint to endpoint model links CO_2 equivalents from IPCC 2007 (Forster et al. 2007) with temperature change and quantifies the contribution of an emission to damage on both human

Table 2 Best available characterization models from midpoint to endpoint

Impact category	Best among existing characterization models	Indicator	Classification
Climate change	Model developed for ReCiPe (De Schryver and Goedkoop 2009a)	Disablilty Adjusted Life Years (DALY) for human health Potentially disappeared fraction of species (PDF m^3 year) for ecosystem health	Interim
Ozone depletion	Model for human health damage developed for ReCiPe (Struijs et al. 2009a)	DALY	Interim
Human toxicity, cancer effects	DALY calculation applied to USEtox midpoint (adapted from Huijbregts et al. 2005)	DALY	II/interim
Human toxicity, non-cancer effects	DALY calculation applied to USEtox midpoint (adapted from Huijbregts et al. 2005)	DALY	Interim
Particulate matter/Respiratory inorganics	Adapted DALY calculation applied to midpoint (adapted from van Zelm et al. 2008, Pope et al. 2002)	DALY	I/II
Ionizing radiation, human health	Frischknecht et al. (2000)	DALY	Interim
Ionizing radiation, ecosystems	None identified		
Photochemical ozone formation	Model for damage to human health as developed for ReCiPe (Van Zelm et al. 2008)	DALY	II
Acidification	Method developed by van Zelm et al. (2007) as in ReCiPe	Potentially disappeared fraction of plant species	Interim
Eutrophication, terrestrial	No methods found		
Eutrophication, aquatic	Model for damage to ecosystem (freshwater only) (Struijs et al. 2009b)	PDF m^3 year	Interim
Ecotoxicity	None identified		
Land use	Model for species diversity loss as in ReCiPe (De Schryver and Goedkoop 2009b)	PDF m^3 year	Interim
Resource depletion, water	None identified		
Resource depletion, mineral and fossil	Method developed for ReCiPe (De Schryver and Goedkoop 2009c; Goedkoop and De Schryver 2009)	Surplus costs	Interim

Only three models are classified above interim, and only these are recommended under the ILCD

health and natural environment. The human health effects included are thermal stress, flooding, malaria, starvation, and diarrhea, while for ecosystem damage, it considers the loss of terrestrial biodiversity. The results of the analysis are summarized in the Electronic supplementary material S4.1.

3.2 Ozone depletion

As for the climate change impact category, there is only one model considered in the evaluation of ozone depletion characterization at midpoint level viz. the ODPs published by the WMO. The recommendation is to use the latest ODP equivalent factors published by the WMO (currently, the 1999 version is recommended, but the changes in the latest update from 2007 (Daniel et al. 2007) are modest for most contributing gases). As for climate change, there are also for ozone depletion factors calculated for different time perspectives. The recommendation is to use the infinite time perspective as represented in the steady-state factors as default, as this is the most widely used practice in policy and also in accordance with the wish in LCIA to catch all impacts of the emissions, also those occurring in the more distant future. The recommended method is classified as level 1 (recommended and satisfactory). The endpoint characterization model of Struijs et al. (2009a, 2010) as implemented in ReCiPe methodology uses the up-to-date AMOUR model (den Outer et al. 2008; van Dijk et al. 2008) to model ozone depletion-related damages to human health, but the model has no links to ecosystem endpoints. This method is identified as the most appropriate at endpoint level, but it is classified as immature for recommendation (interim). The results of the analysis are summarized in the Electronic supplementary material S4.2.

3.3 Human toxicity, cancer, and non-cancer

Several features make USEtox the preferred choice: multimedia models are widely used in LCIA for modeling chemical fate and human exposure, and USEtox reflects the latest consensus amongst modelers. It offers the largest substance coverage with more than 1,250 human toxicological characterization factors and reflects more up-to-date knowledge and data on cancer effect factors than other approaches. The model has been set up to model a global default continent, and it has a nested multimedia model in which it is possible to consider urban, continental, and global-scale differentiation (Rosenbaum et al. 2011). Nevertheless, it has undergone limited testing and shows

Table 3 Distribution of scores against the main criteria for the identified best models at midpoint (across all impact categories)

Score criterion	A	A/B	B	B/C	C	D	E
Completeness of scope	3	4	4	0	4	0	0
Environmental relevance	3	2	6	1	3	0	0
Scientific robustness and certainty	3	0	10	1	1	0	0
Documentation, transparency, and reproducibility	7	1	5	1	1	0	0
Applicability	6	1	6	1	0	0	1
Stakeholder acceptance	2	3	4	2	4	0	0

A full compliance, *B* compliance in all essential aspects, *C* compliance in some aspects (or passable agreement made), *D* little compliance, *E* no compliance

the same fundamental limitations as all simple multimedia models (e.g., uncertainty on degradation half-lives, extrapolation to low doses). USEtox characterization factors are therefore classified as recommended with some improvement needed for most organic chemicals (level II), while factors for metals and for amphiphilics and dissociating organic chemicals are considered as level III (recommended, but to be applied with caution) due to model limitations.

For the midpoint to endpoint characterization, it is proposed as an initial basis to apply average severities for cancer (11.5 disability-adjusted life years (DALY)/case) and non-cancer (2.7 DALY/case) based on Huijbregts et al. (2005). These factors are however considered as immature for recommendation (interim). The results of the analysis are summarized in the Electronic supplementary material S4.3.

3.4 Particulate matter/respiratory inorganics

PM2.5 intake fraction (iF) varies more between low and high population densities (a factor 10 to 100 variation) than between the models themselves (a factor 5 variation). Thus, the ability to differentiate between low and high population densities is a key characteristic before considering the quality of the model itself. Several models enable, in a simplified approach, to calculate the intake fraction, adjusting the population density to be consistent with other human health impacts (e.g., human toxicity, ionizing radiation, etc.). The compilation of Humbert (2009) (based on RiskPoll (Rabl and Spadaro 2004), Greco et al. (2007), USEtox (Rosenbaum et al. 2008), and Van Zelm et al. (2008)) is recommended since it makes a complete assessment of impacts due to primary and secondary PM and differentiates between low and high stacks. It also parameterizes the dominant factors of influence for generic landscape characteristic. At midpoint, intake fraction calculations are classified as level I (recommended and satisfactory) since the human health effects of PM have been extensively studied. USEtox lacks values for secondary particles, but it could be useful to calibrate it and ensure consistency with other impacts on human health.

For the effect and the severity factors, it is recommended to recalculate these starting from the work of van Zelm et al. (2008) that provides a clear framework, but using the most recent epidemiological studies available following the compilation in Humbert (2009). At endpoint, for the effect and severity factor, these effects are well demonstrated for primary particles (level I) but more uncertain for secondary particles (level II, i.e. “recommended but in need of some improvements”). The user must, however, be conscious that the estimated effect of PM may be an indicator of the overall effect of the air pollution rather than based on a proven cause–effect relationship for PM. The results of the analysis are summarized in the Electronic supplementary material S4.4.

3.5 Ionizing radiation, human health

For the midpoint assessment of impact on human health related to the routine releases of radioactive material to the environment, Frischknecht et al. 2000 was the only method

Table 4 Distribution of scores against the main criteria for the identified best models at endpoint (across all impact categories)

Score criterion	A	A/B	B	B/C	C	C/D	D
Completeness of scope	1	0	4	1	3	0	0
Environmental relevance	1	1	4	0	3	0	0
Scientific robustness and certainty	1	0	5	2	1	0	0
Documentation, transparency, and reproducibility	5	0	4	0	0	0	0
Applicability	2	2	5	0	0	0	0
Stakeholder acceptance	0	0	2	1	3	1	2

identified that meets the requirements for a quantitative approach. The fate and exposure model has been based on the ExternE work carried out by Dreicer et al. (1995). At midpoint (e.g., incidences of cancer or other diseases), the method of Frischknecht et al. (2000) is classified as being recommended for human toxicity impacts of ionizing radiation at level II (recommended but in need of some improvements).

At endpoint, no method is recommended due to the high uncertainty on the DALYs per case of severe hereditary effects. The method of Frischknecht et al. (2000), with 61 DALY per case of cancer, can only be used as interim. The results of the analysis are summarized in the Electronic supplementary material S4.5.

3.6 Ionizing radiation, ecosystems

For damage to the ecosystem, the model developed by Garnier-Laplace et al. (2008 and 2009) has been analyzed. It uses the dose rates associated with a 50 % effect during a chronic external gamma irradiation exposure experiment (EDR50, expressed in microgray per hour) (Garnier-Laplace et al. 2009). The ecotoxicological effect factor is calculated by converting the dose rates into the corresponding medium concentration (in water and sediment for freshwaters) for nine commonly adopted reference organisms covering different phyla. The model addresses the freshwater part of the environmental problem, including all vital model elements in a scientifically sound way. This approach for impacts of ionizing radiation is consistent with the treatment of ecotoxicity in USEtox as described by Henderson et al. (2011). The midpoint method for impacts of ionizing radiation is however classified as interim since at the moment, there has been no peer review of the characterization. The method can be evaluated for recommendation, once characterization factors have been adequately reviewed, e.g., through peer-reviewed publication. The results of the analysis are summarized in the Electronic supplementary material S4.5.

3.7 Photochemical ozone formation

For characterization of photochemical impacts at midpoint level, the recommended characterization model is the LOTOS-EUROS model as adapted in van Zelm et al. (2008), modeling tropospheric ozone concentration increase. The recommended characterization model from midpoint to damage builds on the recommended midpoint model and is also documented in van Zelm et al. (2008). At endpoint, it models human health damage in terms of DALYs. No characterization models are recommended for photochemical ozone formation impacts on ecosystems and vegetation.

The LOTOS-EUROS model consists of a detailed fate and exposure model for human health impacts and is developed in a form which makes it readily adaptable for calculation of a set of consistent CFs for each continent if integrating continent-specific atmospheric fate models. Furthermore, the present version of the model can be used to calculate spatially differentiated factors, but only for Europe.

Both midpoint and endpoint characterization models are classified as level II (recommended but in need of some improvements). The results of the analysis are summarized in Supporting information S4.6.

3.8 Acidification

The accumulated exceedance (AE) is to be preferred as default method for midpoint evaluation of acidification. The updated factors provided by Posch and colleagues (2008) should be used. The method is classified as level II (recommended but in need of some improvements). It meets the science-based criteria, and it shows a good stakeholder acceptance as AE-type calculations are used for policy purposes and by the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP). It includes atmospheric and soil fate factors sensitive to emission scenario and distinguishes between load to nonsensitive and sensitive areas. Site-dependent factors are provided on a country level for European countries.

The endpoint method proposed by van Zelm et al. (2007) (ReCiPe) is classified as interim, being the most appropriate among the existing approaches but not sufficient for recommendation. It is a dose–response model of the potentially disappeared fraction of plant species, but it is based on the European forest ecosystem only, and its applicability to other ecosystems still needs to be further explored. The results of the analysis are summarized in Supporting information S4.7.

3.9 Eutrophication

3.9.1 Terrestrial

The recommended method for characterization at midpoint level is the Accumulated Exceedance model as documented in Seppälä et al. (2006) and Posch et al. (2008), modeling the accumulated exceedance of critical loads for nitrogen in sensitive terrestrial ecosystems.

The AE model meets the science-based criteria well and also shows a good stakeholder acceptance as AE-type calculations are used for policy purposes in Europe by the European Commission and by the UNECE LRTAP. It includes atmospheric and soil fate factors sensitive to emission scenario and distinguishes between load to nonsensitive and sensitive areas. It seems to have the strongest potential

for adaptation to other continents to develop consistent characterization factors for each continent (or for a generic continent). The recommendation of the AE model also ensures consistency with the impact category acidification for which it is also recommended at midpoint level. None of the evaluated endpoint characterization models reach a sufficient level of scientific quality to support a recommendation.

3.9.2 Aquatic

The recommended method for characterization at midpoint level applies the CARMEN model for waterborne emissions and the EUTREND model for airborne emissions (Struijs et al. 2009b, 2011) for estimating the residence time of nutrients reaching the freshwater end compartment or marine end compartment. Simplifying a sometimes more complex picture, P is considered the limiting nutrient in freshwater systems and N the limiting nutrient in marine systems.

The recommended approach combines the CARMEN and EUTREND models in a consistent framework presenting the characterization factors as nutrient concentration increases distinguishing aquatic receiving compartments according to the limiting nutrient. Both recommended midpoint models are classified as level II (recommended but in need of some improvements).

At the endpoint, from midpoint to damage, no characterization model is recommended since the best performing available method is classified as interim (Struijs et al. 2009b). The results of the analyses for terrestrial and aquatic eutrophication are summarized in the Electronic supplementary material S4.8 and S4.9.

3.10 Ecotoxicity

USEtox is preferred as the recommended default method for midpoint evaluation of freshwater ecotoxicity. It results from a consensus building effort amongst related modelers, and hence, the underlying principles reflect common and agreed recommendations from these experts. The model accounts for all important parameters in the impact pathway as identified by a systematic model comparison within the consensus process (Rosenbaum et al. 2008; Hauschild et al. 2008). The model addresses the freshwater part of the environmental problem and includes the vital model elements in a scientifically up-to-date way. It provides characterization factors for freshwater ecotoxic impacts for around 2,500 substances. A wider peer review process has been performed through journal peer review and consultation within the UNEP-SETAC Life Cycle Initiative. It has also been set up to model a global default continent—not specifically Europe or North America. USEtox characterization factors are classified as recommended with some improvement needed for most organic chemicals (level II), while factors for metals and for amphiphilics and dissociating organic chemicals are considered as level III (recommended, but to be applied with caution).

3.11 Land use

At midpoint level, the method of Milà i Canals et al. (2007) is recommended for characterizing land use effects at midpoint level. The method is well applicable for agro and forest systems and applies one indicator, namely soil organic matter, which describes the soil quality as a whole. This method is recommended, but to be applied with caution (level III) as it does not cover impacts such as erosion or salinization. At endpoint level, the land use model applied in ReCiPe is identified as the best among the existing, but it is considered immature for recommendation. The method is easy to understand and considers both occupational and transformation effects, and data sources from both mainland Europe and England. However, a peer review of the transformation data is necessary, and the method covers only a limited number of land use types, neglecting essential cause–effect pathways (no primary production or natural landscapes). It does not consider large regional or global effects (such as global extinction versus local reversible losses), misses proper uncertainty data, and lacks regional specific characterization factors covering a global range. Therefore, the ReCiPe method is classified as an interim method, being the most appropriate among the existing approaches but lacking completeness of scope and applicability for recommendation or direct use. The results of the analysis are summarized in the Electronic supplementary material S4.11.

3.12 Resource depletion

Within the analysis of resource depletion models, several questions arose concerning what it is we want to protect within this impact category and which impacts are relevant for the related area of protection. With the current understanding of the Area of Protection Resources, the scarcity of the resource and hence the limitations in its availability to current and future generations were identified as the key concern for this impact category. It was therefore chosen to consider only methods that have an element that reflects the scarcity of the resource and not only look at inherent properties of the abiotic or biotic resource.

Impacts from biotic resource depletions (renewable) are excluded from most impact assessment methods, except for EPS2000 (Steen 1999a, b). This method considers, next to mineral and fossil depletion, impacts from water, wood, and fish depletion, however in a very limited way. Strong research developments and consensus building are needed in this area.

3.12.1 Water

The Swiss Ecoscarcity (water) model is identified as the best among existing models for midpoint characterization of water depletion (at the time of the analysis). Although the method has a very rudimentary environmental model, one could recognize an attempt to differentiate between situations where water extraction causes different levels of damage, and it provides geographically differentiated characterization factors. The model is recommended at level III.

3.12.2 Mineral and fossil (abiotic resources, nonrenewable)

Two types of midpoint methods were distinguished, (1) methods that are at the first step of the impact pathway that connects extractions to the impact on the area of protection, using some inherent property of the material as a basis for the characterization and (2) methods that address the scarcity of the resource by basing the characterization factor on the ratio between what is extracted and what is available to mankind. Regarding the former, an important question is whether any method in this category has sufficient environmental relevance to be recommended, as the factor does not take into account the future scarcity of a resource. Within this assessment of methods, it was chosen not to consider those that do not have an element that reflects the scarcity of the resource. For mineral and fossil resources, the recommendation depends on whether it is preferable to have a robust indicator that does perhaps offer a view on the ultimate availability in the very far future sustainable scenarios, or a much less robust indicator that addresses the actual availability of the resource, under present technological and economic conditions. The CML 2002 method (Guinée et al. 2002) is identified as the best among the existing models and classified as recommended but in need of some improvements (level II).[3]

Of the evaluated endpoint methods, none reached a sufficient level of scientific quality to support a recommendation. Nevertheless, the ReCiPe method for mineral resources (Goedkoop and De Schryver 2009) was identified as the best among existing endpoint models and classified as interim. The method has the rather unique property that it can model resources that are always produced as coproducts. However, the method bases its indicator on metal prices, which are highly fluctuating factors. Next to this, for fossil resources, the damage pathway developed by De Schryver and Goedkoop (2009c) is only developed for oil, while other fossil fuels are simply added by using their energy content as a basis. The results of the analysis are summarized in the Electronic supplementary material S4.12.

[3] This recommendation is not consistent with the scoring of the methods reported in S4.12. After further evaluation and discussions, the scoring of the methods for mineral resources was changed by the EC-JRC on some points prior to the final version of the recommendation report (EC-JRC 2011), but the corresponding scoring table of the recommendation report was not updated to reflect these changes.

4 Discussion and conclusions

The collection of characterization models at midpoint and endpoint levels that are classified as recommended (level I, II, or III) in Tables 1 and 2 represents the EU International Life Cycle Data system, ILCD's recommendations for life cycle impact assessment (EC-JRC 2011). Interim methods are *not* recommended under the ILCD, but they may provide an initial basis for further development.

During the analysis of the existing characterization models, it was evident that LCIA has progressed considerably since the status given by Udo de Haes et al. in 1999, at that time summarizing 3 years of work in the impact assessment working group under SETAC. Midpoint models have been developed towards a much better coverage of the impact pathways, and spatial differentiation is supported by several of them. The competition between midpoint and endpoint methods has developed into a coexistence where the two approaches supplement each other in a consistent impact assessment framework in the most recent LCIA methods. This was also the ambition in the development of recommendations for the ILCD, but the fact that so few endpoint characterization models have matured to a level that supports a proper recommendation makes consistency between midpoint and endpoint recommendations a task of future developments as more endpoint models reach maturity for actual recommendations.

The development towards a stronger representation of geographical or other spatial variability in the models for the regional impact categories comes with a stronger regional association which sometimes makes the choice difficult when emissions from a product system occur in different continents. "Should I choose a North American or a European characterization model for acidification, when my SO_2 emission occurs in China?" As there is no consensus on globally representative characterization models for regional impact categories, we have followed the principle that scientifically robust models based on heterogeneous regions provide a good working basis, i.e., the central-tendency estimate for these smaller regions will be a sufficiently good estimate of a global characterization factor. The models may be continental in scale or even national as long as the region they cover is of an adequate heterogeneity.

The analysis revealed that some impact categories are still not well defined. This was particularly the case for the resource depletion categories, where the analysis was hampered by an insufficient understanding of the Area of Protection "Resources" and hence also of what was really the

issue to address by the characterization modeling of resource use. Other impact categories like noise, accidents, desiccation, and erosion were simply too poorly developed (inventory data are not collected and/or characterization factors are missing) to make a comparative analysis relevant at this stage, regardless that the impacts that they represent can be very important for some product systems.

Another deficiency that became evident in the analysis of the existing characterization models is the poor quality of the information on the uncertainties that is provided for most of the published models. Often, there is no information at all, and when quantitative information is provided, it is often only for some selected aspects of the model. Full quantitative uncertainty estimates are only provided for one impact category, climate change, for the GWPs that are applied for characterization of impacts at midpoint.

5 Outlook

The ILCD recommendations reflect the state of the art 2008–2009 as it is reported in the ILCD document on analysis of existing models (EC-JRC 2010a). Life Cycle Impact Assessment is an active field of research, and for some impact categories, new developments have already been published (e.g., Bayart et al. 2010; Milá i Canals et al. 2009; van Zelm et al. 2011; Pfister et al. 2009; Pfister and Hellweg 2009; Hellweg et al. 2009; Humbert et al. 2011; Gallego et al. 2010; Saad et al. 2011), and on-going research activities address some of the shortcomings identified together with the recommendations and classifications (in EC-JRC 2011). While it is preferable with a certain stability of LCIA methods, it is also foreseeable that updates of these recommendations will be needed in some years.

In our internationalized economy, product systems are often global in geographic scope, even for simple products, and this means that a recommended LCIA method should have a global coverage and validity. Regional characterization models have been developed for North America (TRACI, LUCAS), Japan (LIME), and Europe (numerous), and most of the recommended methods in the ILCD system are European in scope. The European continent is so large and heterogeneous that the European-based characterization factors may be expected to serve as reasonable proxies also for other continents. Nevertheless, there are some of the midpoint impact categories for which characterization factors could come out differently for other continents if these were to be modeled using the recommended models (notably ozone formation, freshwater eutrophication and perhaps marine eutrophication, acidification, and respiratory inorganics). An important step forward will be the development of global models for regional impact categories, ensuring scientifically valid characterization results that can be aggregated across the life cycle regardless where the emissions occur.

For the endpoint models, the evaluation only judges few to be of sufficient quality for an ILCD recommendation (namely human toxicity—cancer effect, particulate matter, and photochemical ozone formation). Most of the models that have qualified as the best among the existing are still at a level where they are classified as interim and not mature for recommendation. The complexity and inherent uncertainties of endpoint modeling are clearly larger than for midpoint modeling, but the poor classifications also reflect the fact that endpoint modeling is still a new field in LCIA as well as in environmental modeling in general. There is a need for much more research before methods can be recommended for endpoint modeling across all impact categories.

Also the consistency between characterization at midpoint level and characterization from midpoint to endpoint level is an issue, in particular when different models from different methods are attempted combined as has been the case in our endeavor. The consistency is in practice only well ensured when midpoint and endpoint methods are developed to serve in the same framework covering the whole impact pathway from emission to area of protection. This is the case for several of the more recent impact assessment methodologies (e.g., LIME and ReCiPe) that aim to address all impacts at both midpoint and endpoint levels.

In order to facilitate the interpretation of the results, it is useful to express the different indicator scores in the impact profile in the same metric and bring them on a common scale, particularly for the impact assessment at midpoint with its many impact categories. This is the purpose of the normalization step, and it requires the development of a consistent set of normalization references for the ILCD characterization methods by applying the recommended characterization factors on a consistent set of inventory data, e.g., representing the annual per capita emissions from Europe or the world.

For the impact categories human toxicity and ecotoxicity, the number of chemical substances used in industrial production is so high that even with the latest developments (www.usetox.org), the number of characterization factors offered by the recommended characterization model USEtox™ will often be insufficient to ensure a satisfactory coverage of the inventory flows. There is thus a need to address the substance data shortage and calculate characterization factors for many new substances.

With the growth in the number of characterization models available, the choice has not become easier for the LCA practitioner since the attempt to describe best practice by Udo de Haes et al. (1999), but our analysis has shown that there are real differences in terms of scientific validity among existing and used characterization models. Some

models perform better than others in meeting the scientific and stakeholder acceptance criteria established here, and this has been the basis supporting the development of the ILCD recommendations that will help guide the LCA practitioner.

Acknowledgments The research was partly funded by the European Commission through a service contract (no. 383163) and by a research project under the seventh Framework Program on Environment (ENV.2008.3.3.2.1: PROSUITE—Sustainability Assessment of Technologies, grant agreement no. 227078).

References

Bare JC, Pennington DW, Udo de Haes HA (1999) Life cycle impact assessment sophistication—international workshop. Int J Life Cycle Assess 4(5):299–306

Bare JC, Hofstetter P, Pennington DW, de Haes HA U (2000) Life cycle impact assessment midpoints vs. endpoints: the sacrifices and the benefits. Int J Life Cycle Assess 5(5):319–326

Bare JC, Norris GA, Pennington DW, McKone T (2003) TRACI, the tool for the reduction and assessment of chemical and other environmental impacts. J Ind Ecol 6(3–4):49–78

Bayart J-B, Bulle C, Deschênes L, Margni M, Pfister S, Vince F, Koehler A (2010) A framework for assessing off-stream freshwater use in LCA. Int J Life Cycle Assess 15(5):439–453

Daniel JS, Velders GJM et al. (2007) Halocarbon scenarios, ozone depletion potentials, and global warming potentials. Chapter 8 in Scientific assessment of ozone depletion: 2006, Global Ozone Research and Monitoring Project—report no. 50. World Meteorological Organization, Geneva, Switzerland

De Schryver A, Goedkoop MJ (2009a) Climate change. Chapter 3. In: Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

De Schryver A, Goedkoop MJ (2009b) Land use. Chapter 10. In: Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

De Schryver A, Goedkoop MJ (2009c) Mineral Resource. Chapter 12. In: Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

Den Outer PN, van Dijk A, Slaper H (2008) Validation of ultraviolet radiation budgets using satellite observations from the OMI instrument. RIVM Report no 610002002, Bilthoven, The Netherlands, pp 59

Dreicer M, Tort V, Manen P (1995) ExternE, externalities of energy, vol. 5 9 Nuclear, Centr d'étude sur l'Evaluation de la Protection dans le domaine 10 nucléaire (CEPN). In: European Commission DGXII (ed) Science, 11 Research and development JOULE, Luxembourg

Dreyer LC, Niemann AL, Hauschild MZ (2003) Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. Does it matter which one you choose? Int J Life Cycle Assess 8(4):191–200

EC-JRC (2010a) Analysis of existing environmental impact assessment methodologies for use in life cycle assessment—background document. ILCD Handbook—International Reference Life Cycle Data System, European Union. At http://lct.jrc.ec.europa.eu/assessment/assessment/projects#consultation_impact – accessed January 2012

EC-JRC (2010b) Framework and requirements for LCIA models and indicators. ILCD Handbook—International Reference Life Cycle Data System, European Union EUR24586EN. ISBN 978-92-79-17539-8. At http://lct.jrc.ec.europa.eu/assessment/assessment/projects#consultation_impact – accessed January 2012

EC-JRC (2011) Recommendations based on existing environmental impact assessment models and factors for life cycle assessment in European context. ILCD Handbook—International Reference Life Cycle Data System, European Union EUR24571EN. ISBN 978-92-79-17451-3. At http://lct.jrc.ec.europa.eu/assessment/assessment/projects#consultation_impact – accessed January 2012

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. Chapter 2. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Frischknecht R, Braunschweig A, Hofstetter P, Suter P (2000) Modelling human health effects of radioactive releases in life cycle impact assessment. Environ Impact Assess Rev 20(2):159–189

Frischknecht R, Steiner R, Jungbluth N (2008) Methode der ökologischen Knappheit—Ökofaktoren 2006, ö.b.u. und Bundesamt für Umwelt, Bern

Gallego A, Rodriguez L, Hospido A, Moreira MT, Feijoo G (2010) Development of regional characterisation factors for aquatic eutrophication. Int J Life Cycle Assess 15:32–43

Garnier-Laplace JC, Beaugelin-Seiller K, Gilbin R, Della-Vedova C, Jolliet O, Payet J (2008) A screening level ecological risk assessment and ranking method for liquid radioactive and chemical mixtures released by nuclear facilities under normal operating conditions. Proceedings of the International conference on Radioecology and Environmental Protection, 15–20 June 2008, Bergen

Garnier-Laplace JC, Beaugelin-Seiller K, Gilbin R, Della-Vedova C, Jolliet O, Payet J (2009) A screening level ecological risk assessment and ranking method for liquid radioactive and chemical mixtures released by nuclear facilities under normal operating conditions. Radioprotection 44(5):903–908

Goedkoop MJ, De Schryver A (2009) Fossil resource. Chapter 13. In: Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

Goedkoop MJ, Spriensma R (2000) Eco-indicator 99, a damage oriented method for lifecycle impact assessment, methodology report (update April 2000)

Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008—a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

Greco S, Wilson A, Spengler J, Levy J (2007) Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States. Atmos Environ 41(5):1011–1025

Guinée JB (ed), Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn JA, van Duin R, Huijbregts MAJ (2002) Handbook on life cycle assessment: operational guide to the ISO standards. Series: eco-efficiency in industry and science. Kluwer Academic Publishers, Dordrecht (Hardbound, ISBN 1-4020-0228-9; Paperback, ISBN 1-4020-0557-1)

Hauschild M, Potting J (2005) Spatial differentiation in life cycle impact assessment—the EDIP2003 methodology. Environmental News no. 80. The Danish Ministry of the Environment, Environmental Protection Agency, Copenhagen

Hauschild MZ, Huijbregts M, Jolliet O, MacLeod M, Margni M, van de Meent D, Rosenbaum RK, McKone T (2008) Building a model based on scientific consensus for life cycle impact assessment of chemicals: the search for harmony and parsimony. Environ Sci Technol 42(19):7032–7037

Hellweg S, Demou E, Bruzzi R, Meijer A, Rosenbaum RK, Huijbregts MAJ, Mckone TE (2009) Integrating human indoor air pollutant exposure within life cycle impact assessment. Environ Sci Technol 43(6):1670–1679

Henderson A, Hauschild M, Van de Meent D, Huijbregts MAJ, Larsen HF, Margni M, McKone TE, Payet J, Rosenbaum RK, Jolliet O (2011) USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in LCA. Int J Life Cycle Assess 16(8):701–709

Huijbregts MAJ, Rombouts LJA, Ragas AMJ, Van de Meent D (2005) Human-toxicological effect and damage factors of carcinogenic and noncarcinogenic chemicals for life cycle impact assessment. Integr Environ Assess Manag 1:181–244

Humbert S (2009) Geographically differentiated life-cycle impact assessment of human health. Doctoral dissertation, University of California, Berkeley, Berkeley, California, USA

Humbert S, Marshall JD, Shaked S, Spadaro J, Nishioka Y, Preiss P, McKone TE, Horvath A, Jolliet O (2011) Intake fraction for particulate matter: recommendations for life cycle assessment. Environ Sci Technol 45(11):4808–4816

ISO (2006) ISO 14044:2006 Environmental management—life cycle assessment—requirements and guidelines. International Standards Organization

Itsubo N, Sakagami M, Washida T, Kokubu K, Inaba A (2004) Weighting across safeguard subjects for LCIA through the application of conjoint analysis. Int J Life Cycle Assess 9(3):196–205

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8(6):324–330

Jolliet O, Müller-Wenk R, Bare JC, Brent A, Goedkoop M, Heijungs R, Itsubo N, Peña C, Pennington D, Potting J, Rebitzer G, Stewart M, Udo de Haes H, Weidema B (2004) The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. Int J Life Cycle Assess 9(6):394–404

Margni M, Gloria T, Bare J, Seppälä J, Steen B, Struijs J, Toffoletto L, Jolliet O (2007) Guidance on how to move from current practice to recommended practice in life cycle impact assessment: UNEP/SETAC life cycle initiative

Milà i Canals L, Romanyà J, Cowell SJ (2007) Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in life cycle assessment (LCA). J Clean Prod 15:1426–1440

Milà i Canals L, Chenoweth J, Chapagain A, Orr S, Antón A, Clift R (2009) Assessing freshwater use impacts in LCA. Int J Life Cycle Assess 14(1):28–42

Montzka SA, Fraser PJ (1999) Controlled substances and other source gases. Chapter 2 in scientific assessment of ozone depletion: 1998, Global Ozone Research and Monitoring Project—report no. 44, World Meteorological Organization, Geneva, Switzerland

Pant R, Van Hoof G, Schowanek D, Feijtel TCJ, de Koning A, Hauschild MZ, Pennington DW, Olsen SI, Rosenbaum R (2004) Comparison between three different LCIA methods for aquatic ecotoxicity and a product environmental risk assessment—insights from a detergent case study within OMNIITOX. Int J Life Cycle Assess 9 (5):295–306

Payet J (2004) Assessing toxic impacts on aquatic ecosystems in LCA. PhD thesis 3112, Ecole Polytechnique Fédérale de Lausanne

Pfister S, Hellweg S (2009) The water "shoesize" vs. footprint of bioenergy. Letter PNAS 106(35):E93–E94

Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43(11):4098–4104

Pizzol M, Christensen P, Schmidt J, Thomsen M (2011a) Impacts of "metals" on human health: a comparison between nine different methodologies for life cycle impact assessment (LCIA). J Clean Prod 19:646–656

Pizzol M, Christensen P, Schmidt J, Thomsen M (2011b) Eco-toxicological impact of "metals" on the aquatic and terrestrial ecosystem: a comparison between eight different methodologies for life cycle impact assessment (LCIA). J Clean Prod 19:687–698

Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. J Am Med Assoc 287:1132–1141

Posch M, Seppälä J, Hettelingh JP, Johansson M, Margni M, Jolliet O (2008) The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int J Life Cycle Assess 13(6):477–486

Rabl A, Spadaro JV (2004) The RiskPoll software, version is 1.051 (dated August 2004). www.arirabl.com – accessed January 2012

Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Köhler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess 13(7):532–546

Rosenbaum RK, Huijbregts M, Henderson A, Margni M, McKone TE, van de Meent D, Hauschild MZ, Shaked S, Li DS, Slone TH, Gold LS, Jolliet O (2011) USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. Int J Life Cycle Assess 16(8):710–727

Saad R, Margni M, Koellner T, Wittstock B, Deschênes L (2011) Assessment of land use impacts on soil ecological functions: development of spatially differentiated characterization factors within a Canadian context. Int J Life Cycle Assess 16(3):198–211

Seppälä J, Posch M, Johansson M, Hettelingh JP (2006) Country-dependent characterization factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. Int J Life Cycle Assess 11(6):403–416

Steen B (1999a) A systematic approach to environmental priority strategies in product development (EPS). Version 2000-general system characteristics; CPM report 1999:4, Chalmers University of Technology, Gothenburg, Sweden

Steen B (1999b) A systematic approach to environmental priority strategies in product development (EPS). Version 2000-models and data of the default method; CPM report 1999:5, Chalmers University of Technology, Gothenburg, Sweden

Struijs J, van Wijnen HJ, van Dijk A, Huijbregts MAJ (2009a) Ozone layer depletion. Chapter 4. In: Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.

Report I: Characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

Struijs J, Beusen A, van Jaarsveld H, Huijbregts MAJ (2009b) Aquatic eutrophication. Chapter 6. In: Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: characterisation, first edition, 6 January 2009, http://www.lcia-recipe.net – accessed January 2012

Struijs J, van Dijk A, Slaper H, van Wijnen HJ, Velders GJM, Chaplin G, Huijbregts MAJ (2010) Spatial- and time-explicit human damage modeling of ozone depleting substances in life cycle impact assessment. Environ Sci Technol 44(1):204–209

Struijs J, Beusen A, de Zwart D, Huijbregts M (2011) Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment. Int J Life Cycle Assess 16(1):59–64

Toffoletto L, Bulle C, Godin J, Reid C, Deschênes L (2007) LUCAS—a new LCIA method used for a Canadian-specific context. Int J Life Cycle Assess 12(2):93–102

Udo de Haes HA, Jolliet O, Finnveden G, Hauschild M, Krewitt W, Müller-Wenk R (1999) Best available practice regarding impact categories and category indicators in life cycle impact assessment. Background document for the Second Working Group on Life Cycle Impact Assessment of SETAC-Europe (WIA-2). Int J Life Cycle Assess 4(2):66–74 and 4(3):167–174

Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich E, Hofstetter P, Klöpffer W, Krewitt W, Lindeijer E, Jolliet O, Mueller-Wenk R, Olsen S, Pennington D, Potting J, Steen B (eds) (2002) Life cycle impact assessment: striving towards best practice. SETAC Press, Pensacola, ISBN 1-880611-54-6

Van Dijk A, Den Outer PN, Slaper H (2008) Climate and Ozone change Effects on Ultraviolet radiation and Risks (COEUR) using and validating earth observations; RIVM Report 61000 2001/2008; Bilthoven, The Netherlands, 2008

Van Zelm R, Huijbregts MAJ, Van Jaarsveld HA, Reinds GJ, De Zwart D, Struijs J, Van de Meent D (2007) Time horizon dependent characterization factors for acidification in life-cycle assessment based on forest plant species occurrence in Europe. Environ Sci Technol 41(3):922–927

Van Zelm R, Huijbregts MAJ, Den Hollander HA, Van Jaarsveld HA, Sauter FJ, Struijs J, Van Wijnen HJ, Van de Meent D (2008) European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmos Environ 42:441–453

Van Zelm R, Schipper AM, Rombouts M, Snepvangers J, Huijbregts MAJ (2011) Implementing groundwater extraction in life cycle impact assessment: characterization factors based on plant species richness. Environ Sci Technol 45(2):629–635